REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
07-07-2015	Final Report	1-Aug-2014 - 30-Apr-2015

4. TITLE AND SUBTITLE

Final Report: Research Area 4: Electronics: Study of defect levels in InAs/InAsSb type-II superlattice using pressure-dependent photoluminescence

5a. CONTRACT NUMBER
W911NF-14-1-0388

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS

Yong-Hang Zhang

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES

Arizona State University
P.O. Box 876011

Tempe, AZ 85287 -6011

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)

U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
65929-EL-II.2

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

We have performed pressure-dependent PL measurements on an InAs/InAs0.86 Sb0.14 T2SL structure. By fitting the measured peak energy shift and observing a quenching of the PL intensity we have determined a crossover pressure at which we believe the T2SL electron confined state reaches that of a defect level in the superlattice. This change in nature from a radiative to non-radiative recombination mechanism with pressure is confirmed from power dependent PL measurements. We also examined the thermal activation energies at ambient pressure and close to the crossover pressure. These results support and are consistent with the determined values for the pressure

15. SUBJECT TERMS

defect levels; T2SL; pressure-dependent photoluminescence

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Yong-Hang Zhang
					19b. TELEPHONE NUMBER 480-/72-7279

Report Title

Final Report: Research Area 4: Electronics: Study of defect levels in InAs/InAsSb type-II superlattice using pressure-dependent photoluminescence

ABSTRACT

We have performed pressure-dependent PL measurements on an InAs/InAs0.86 Sb0.14 T2SL structure. By fitting the measured peak energy shift and observing a quenching of the PL intensity we have determined a crossover pressure at which we believe the T2SL electron confined state reaches that of a defect level in the superlattice. This change in nature from a radiative to non-radiative recombination mechanism with pressure is confirmed from power dependent PL measurements. We also examined the thermal activation energies at ambient pressure and close to the crossover pressure. These results support and are consistent with the determined values for the pressure coefficients of the valence and conduction band edges of the structure and the defect level. As a result, these experiments provide strong evidence that the defect level is approximately 180 meV above the conduction band edge of InAs. Consequently, these findings explain why Ga-free T2SL structures have much longer minority carrier lifetimes, a highly desirable advantage for both mid-wave and long-wave IR photodetector applications.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
07/07/2015	1.00	M. K. Lewis, A. D. Prins, Z. L. Bushell, S. J. Sweeney, S. Liu, Y.-H. Zhang. Evidence for a defect level above the conduction band edge of InAs/InAsSb type-II superlattices for applications in efficient infrared photodetectors, Applied Physics Letters, (04 2015): 0. doi: 10.1063/1.4919549

TOTAL: 1

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

Strong experimental evidence for the existence of above conductance band deflect level.

By fitting the measured peak energy shift and observing a quenching of the PL intensity we have determined a crossover pressure at which we believe the T2SL electron confined state reaches that of a defect level in the superlattice.

These experiments provide strong evidence that the defect level is approximately 180 meV above the conduction band edge of InAs. Consequently, these findings explain why Ga-free T2SL structures have much longer minority carrier lifetimes, a highly desirable advantage for both mid-wave and long-wave IR photodetector applications.

Technology Transfer

The final report for

Research Area 4: Electronics: Study of defect levels in InAs/InAsSb type-II superlattice using pressure-dependent photoluminescence

(Contract number: W911NF-14-1-0388)

July 7, 2015

ARO Grants Officer's Representative: Dr. William W. Clark

Tel: (919) 549-4314,

Email: william.w.clark9.civ@mail.mil

PI: Yong-Hang Zhang

Director

Center for Photonics Innovation

&

Professor

School of Electrical, Computer, and Energy Engineering

Arizona State University

Tempe, AZ 85287

Tel: 480-965-2562

Fax: 480-965-0775

Email:yhzhang@asu.edu

Project Objectives

- The objective of this project was to find experimental evidence to confirm that the defect energy levels are inside the conduction band of the Ga-free T2SLs. The approach used took advantage of a physical effect, that applying hydrostatic pressure to III-V semiconductors causes a strong and reversible change in the electronic band-structure [1].
- Of most relevance to this study, the conduction band edge moves upwards in energy at a typical rate of ≈100 meV·GPa^{-1} for III-V semiconductors [2]. This manifests itself very clearly through an increase in bandgap and consequently, an increase in the optical transition energy with increasing pressure. In contrast, localized states such as defect energy states, are typically pressure insensitive owing to the fact that they are strongly localized and decoupled from the periodicity of the crystal [3]. It is therefore possible to use high pressure to probe the interaction between the band edges and defect energy states, which for example, may be seen through the quenching of photoluminescence or in an abrupt increase in the dark current of a photodetector due to increased non-radiative recombination.
- When those defect energy levels appear in the bandgap under certain hydrostatic pressure, the PL intensity as well as minority carry lifetime were expected to decrease substantially. In contrast, since the defect energy levels in the conventional T2SLs lie already inside the forbidden gap, both PL intensity as well as the minority carrier lifetime are not expected to exhibit dramatic change [1]. See figure 1.

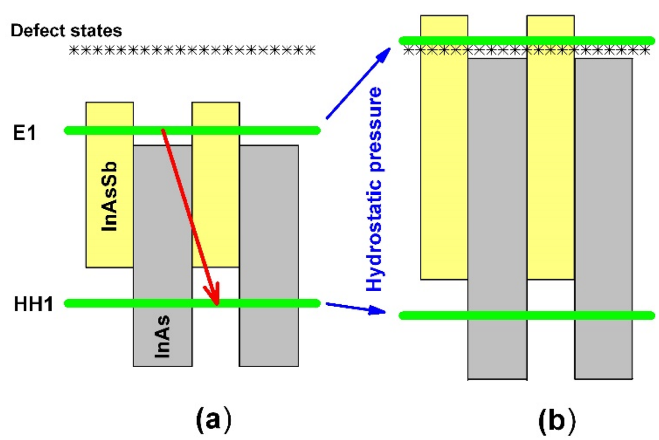

FIG. 1. (a) A schematic band edge diagram for a Ga-free InAs/InAsSb T2SL showing a defect state above the conduction band edge; (b) Under hydrostatic pressure the effective bandgap energy increases, mainly due to an upward shift in the conduction band edge, while the defect states remain at the same energy. Quenching of the photoluminescence happens when the electron miniband edge moves close to the defect energy level. (Figure from ref. [4]).

Key Results Summary

- We have performed pressure-dependent PL measurements on an $InAs/InAs_{0.86}Sb_{0.14}$ T2SL structure [4].
- By fitting the measured peak energy shift and observing a quenching of the PL intensity we have determined a crossover pressure at which we believe the T2SL electron confined state reaches that of a defect level in the superlattice. This change in nature from a radiative to non-radiative recombination mechanism with pressure is confirmed from power dependent PL measurements [4].
- We also examined the thermal activation energies at ambient pressure and close to the crossover pressure. These results support and are consistent with the determined values for the pressure coefficients of the valence and conduction band edges of the structure and the defect level. As a result, these experiments provide strong evidence that the defect level is approximately 180 meV above the conduction band edge of InAs [4].
- Consequently, these findings explain why Ga-free T2SL structures have much longer minority carrier lifetimes, a highly desirable advantage for both mid-wave and long-wave IR photodetector applications [4].

Detailed Results

- Four separate pressure runs were carried out with most of the data being taken with increasing pressure, each cycle gave good agreement [4]. Figure 2(a) shows corrected PL spectra from one pressure run up to 2.16 GPa. Increased noise in the PL signal was seen over the range from 0.34 eV to 0.44 eV due to the absorption of the pressure medium over this wavelength range as shown in Figure 2(b). The interpolated transmission data [5] from liquid methanol and ethanol based on the 4:1 mixture ratio at 300K (solid line) and the data from ethanol under pressure [6] and frozen methanol spectra [7] are used to estimate the shift and transmission behavior up to 2.16 GPa (dashed line). Based on this evidence it is clear that the transmission data changes with pressure, but whilst it was not possible for us to carry out a dynamic correction at each pressure and temperature we are able to show that the absorption should have little effect above 0.46 eV; this is confirmed by PL spectra from the InGaAsP pressure gauge [4].

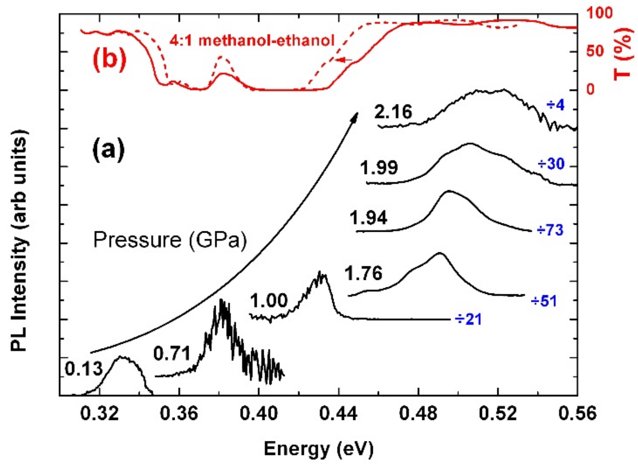

FIG. 2. (a) Photoluminescence spectra acquired from one run at different hydrostatic pressures up to 2.16 GPa. (b) On the same energy axis the optical transmission "T" (from 0 to 100%) of the methanol-ethanol pressure transmitting media calculated from literature data at 0 GPa (solid line), the arrow indicates the shift to the estimated transmission at 2.16 GPa (dashed line). Figure from ref. [4].

- The PL full width half maximum (FWHM) of the T2SL peak was 20 meV at an estimated excitation density of 13 $W \cdot cm^{-2}$ and decreased approximately linearly to around 15 meV at 1.5 GPa, above this it increased approximately linearly reaching 40 meV at 2.16 GPa [4]. Figure 3(a) shows the collected peak emission energy data against pressure, which when fitted gives a pressure coefficient of 93 ± 4 $meV \cdot GPa^{-1}$. This value is close to the quoted value of 96-108 $meV \cdot GPa^{-1}$ for InAs [8] and 128-155 $meV \cdot GPa^{-1}$ for InSb [8]. Calculations based on this structure using Nextnano software [9] and taking into account bandgap and effective mass changes, show that the confinement energy of the electron states changes by as little as 1 meV up to 2.16 GPa [4]. The change in strain is negligible as the two constituent layers of the T2SL have similar elastic constants. The initial electron confinement is calculated as 18 meV in the superlattice well of depths of 80 meV. This well depth deepens slightly with pressure but importantly the electron miniband is expected to shift at the same rate as the InAs layer.

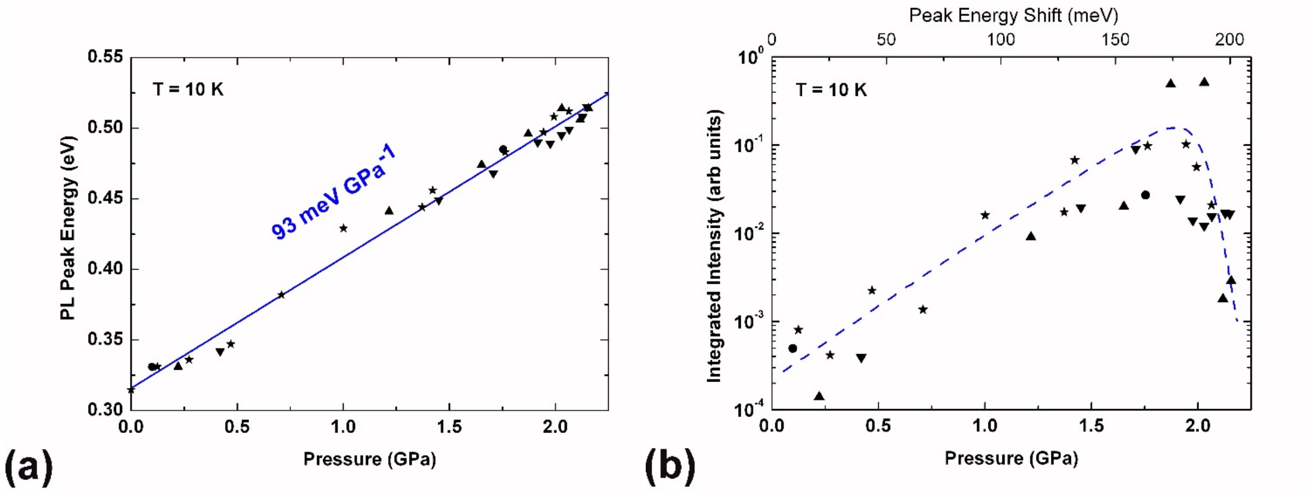

FIG. 3. (a) A linear fit of the photoluminescence peak energy data obtained for the T2SL sample from the four pressure runs indicated using four different symbols. (b) The integrated photoluminescence intensity of the T2SL sample plotted as a function of pressure and also peak energy shift from ambient pressure on the top axis. The dashed line is drawn as a guide to the eye. (Figure from ref. [4]).

- Figure 3(b) shows all of the integrated PL intensity data corrected for the system response and optical collection efficiency from the four pressure runs as a function of pressure and peak energy shift [4]. An energy level crossover between a defect energy level (or another conduction band minima) and a conduction band edge state is normally accompanied by a strong decrease in the integrated PL intensity as seen in InAs/GaAs quantum dots undergoing a Γ- X crossover [10] and may also give rise to new radiative peaks moving with different or negative pressure coefficients [10, 11]. Figure 3(b) shows such a decrease in PL intensity but we report no change in the pressure coefficient of the PL peak energy associated with this quenching nor any new radiative peaks above the crossover pressure [4]. All these characteristics are expected in the case of a crossover with a non-radiative defect level. PL was not observed above the pressures shown in Figure 3(b) as the defect energy levels move below the conduction band edge and into the InAs bandgap becoming SRH recombination centers.
- A careful comparison of the energy and intensity data shown in Figure 3(b) and those reported by Itskevich *et al* [10] and elsewhere indicates a crossover at 2 GPa. This corresponds to a PL energy shift of 0.186 eV (onset at 1.92 GPa with the true crossover close to 2 GPa, giving 1.96 ± 0.04 GPa or an energy shift of ~0.18 ± 0.01 eV) [4]. According to Daunov *et al* [12] the ratio of the pressure coefficients of the conduction and valence band edges for many III-V semiconductors (including InSb) are equal to ~7. For our structure this would mean that 82 meV·GPa^{-1} of the determined pressure coefficient of our sample would go into the conduction band edge with the valence band edge moving down at a rate of -11 meV·GPa^{-1} [4]. Assuming that the defect energy level

does not move with pressure, as shown in Figure 1, using the above conduction band edge shift over 2 GPa and adding the 17 meV confinement energy at 2 GPa leads to a determined defect level ~0.18 eV above the InAs conduction band edge at ambient pressure. More details about this assignment will be discussed further below.

- The PL intensity data as a function of laser excitation power and temperature under pressure are plotted in Figure 4 and examined to confirm that the PL quenching at 2 GPa is indeed due to a change from a radiative dominant recombination process to a non-radiative dominant recombination mechanism [4]. Figure 4(a) shows the excitation power dependence of the T2SL integrated PL intensity data at 0, 0.42, 1.87 and 2.16 GPa at 10K.

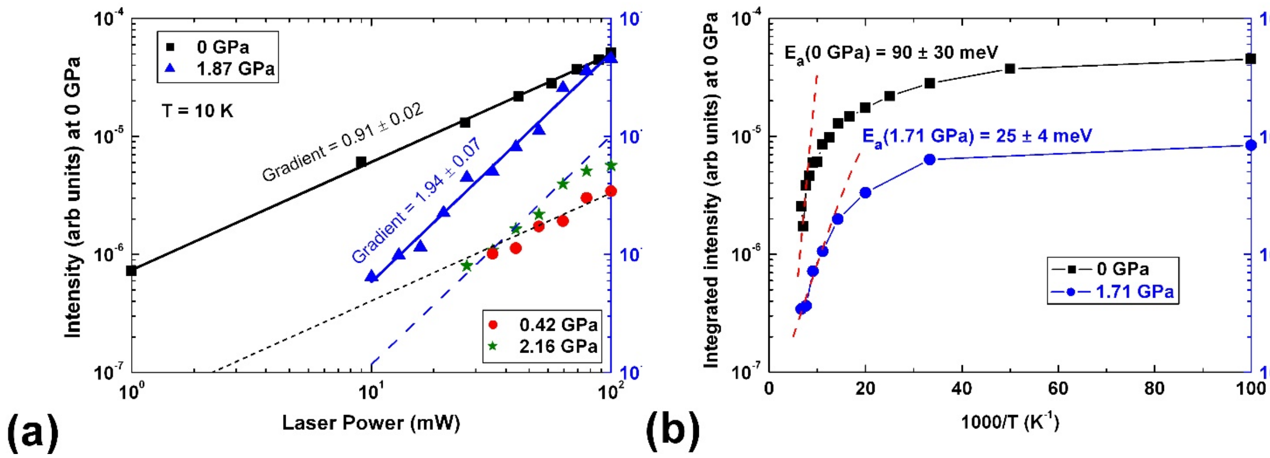

FIG. 4. (a) Power dependent PL measurements taken at 0 GPa (intensity axis on left), and 0.42, 1.87 and 2.16 GPa (intensity axis on right). Solid lines show linear fits of the PL intensity at 0 and 1.87 GPa. Dotted and broken lines are the same fits offset as a guide to the eye at 0.42 GPa and 2.16 GPa respectively. (b) Arrhenius plots of data at 0 GPa (left intensity axis) and 1.71 GPa (right intensity axis). Dashed lines in the high temperature range are marked with the determined activation energy (E_a) in meV. (Figure from ref. [4]).

- The observed PL intensity as a function of excitation power density is easily described by a power law with a fitted power exponent at 0 GPa of 0.91, close to 1, which, for an undoped sample, such as that discussed in ref. [4], clearly indicates a dominant radiative recombination process [13, 14]. A similar gradient is seen at 0.42 GPa, confirming that the recombination is radiative in nature and that mid gap SRH recombination is negligible at low pressure [4]. At 1.87 GPa (the onset of the high pressure PL intensity decline) the measured gradient is 1.94. This value is close to 2, which indicates a dominant non-radiative, defect-related recombination path is now involved. Finally at 2.16 GPa a gradient close to 1.94 is seen but with possible evidence of saturation at the highest laser power. All the data in Figure 4(a) confirm our expectation that the PL

quenching at 2 GPa is the result of a transition from dominant radiative recombination to dominant non-radiative recombination.

- Assuming that the non-radiative recombination can also be thermally activated we studied the integrated PL intensity quenching from 10K to 150 K at 0 GPa and 1.71 GPa and the measured results are shown in Figure 4(b) [4]. At high pressure and over this low temperature range it should be noted that the pressure medium remains solid and the pressure is constant within the SBC.
- From Figure 4(b), ref. [4], it can be seen that the higher temperature behavior of each data set follows an exponential dependence [15], from which activation energies have been calculated. The 0 GPa data gives an activation energy of 90 ± 30 meV, but at 1.71 GPa a much lower value of 25 ± 4 meV is obtained [4]. Our measured activation energy of 90 meV at 0 GPa may be related to the depth of the electron well (80 meV). At 1.71 GPa it is 0.29 GPa from our determined crossover pressure (2 GPa) and using our conduction band edge pressure coefficient of 82 $meV \cdot GPa^{-1}$ we estimate that the energy level associated with the quenching is ~24 meV away. This data confirms our assumptions of the pressure-dependent energy shifts of the valence band and conduction band edges. It also points to the fact that the defect level is indeed not moving with pressure, as if it were then the activation energy obtained at 1.71 GPa would not be consistent with our results as the rate at which the confined electron state approached the defect would depend on both pressure coefficients. We note here that the nature and exact identification of these defect states is outside of the scope of this present work, but will be investigated in the future studies.

Conclusions

- Strong experimental evidence for the existence of above conductance band deflect level.
- By fitting the measured peak energy shift and observing a quenching of the PL intensity we have determined a crossover pressure at which we believe the T2SL electron confined state reaches that of a defect level in the superlattice [4].
- These experiments provide strong evidence that the defect level is approximately 180 meV above the conduction band edge of InAs. Consequently, these findings explain why Ga-free T2SL structures have much longer minority carrier lifetimes, a highly desirable advantage for both mid-wave and long-wave IR photodetector applications [4].

Bibliography

[1] Y.-H. Zhang, ARO pressure dependent PL Project Description (Technical Proposal) final.
[2] A. Prins, A. Adams, and S. Sweeney, "Semiconductor Research Experimental Techniques", Vol. 150, Chap. 6 "Pressure Studies", edited by A. Patane and N. Balkan (Springer, Heidelberg, Germany, 2012).

[3] R-D. Hong, D. W. Jenkins, S. Y. Ren, and J. D. Dow, Phys. Rev. B 38, 12549 (1988).
[4] A. Perins, M. Lewis, Z. Bushell, S. Sweeney, S. Liu and Y-H. Zhang. "Evidence for a defect level above the conduction band edge of InAs/InAsSb type-II superlattices for applications in efficient infrared photodetectors", APL, 106, 17, (2015).
[5] E. K. Plyler, J. Res. Nat. Bur. Stand. Vol. 48, 281 (1952).
[6] A. Anderson, J. Benson, and W. Smith, Spectros. Lett. 31, 369 (1998).
[7] M. Falk and E. Whalley, J. Chem. Phys. 54, 4863 (1971).
[8] P. E. Van Camp, V. E. Van Doren, and J. T. Devreese, Phys. Rev. B 41, 1598 (1990).
[9] Nextnano Semiconductor Software Solutions, http://www.nextnano.de
[10] I. E. Itskevich, S. G. Lyapin, I. A. Troyan, P. C. Klipstein, L. Eaves, P. C. Main, and, M. Henini, Phys. Rev. B 58, R4250 (1998).
[11] X. Liu, M.-E. Pistol, L. Samuelson, S. Schwetlick, and W. Seifert, Appl. Phys. Lett. 56, 1451 (1990).
[12] M. I. Daunov, I. K. Kamilov, S. F. Gabibov, and A. B. Magomedov, Phys. Stat. Sol. (b) 235, No. 2, 297– 301 (2003).
[13] W. Feng, Y. Wang, J. Wang, W. K. Ge, Q. Huang, and J. M. Zhou, Appl. Phys. Lett. 72, 1463 (1998).
[14] X. Chen, Y. Zhou, L. Zhu, Z. Qi, Q. Xu, Z. Xu, S. Guo, J. Chen, L. He, and J. Shao, Jpn. J. Appl. Phys. 53, 082201 (2014).
(15) J. L. Pankove, Optical Processes in Semiconductors, pp. 165–166. (Dover, New York, 1971).